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Abstract. Neutron capture for incident neutron energies <1eV up to 100 keV has been measured for ^{151,153}Eu targets. The highly efficient DANCE (Detector for Advanced Neutron Capture Experiments) array coupled with the intense neutron beam at Los Alamos Neutron Science Center is used for the experiment. Stable Eu isotopes mass separated and electroplated on Be backings were used. Properties of well-resolved, strong resonances in two Eu nuclei are examined. The parameters for most of these resonances are known. Detailed multiplicity information for each resonance is obtained employing the high granularity of the DANCE array. The radiative decay cascades corresponding to each resonance are obtained in the experiment. The measurements are compared to simulation of these cascades which calculated with various models for the radiative strength function. Comparison between the experimental data and simulation provides an opportunity to investigate the average quantities.

Keywords: neutron capture, radiative strength function, resonances.
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I. INTRODUCTION

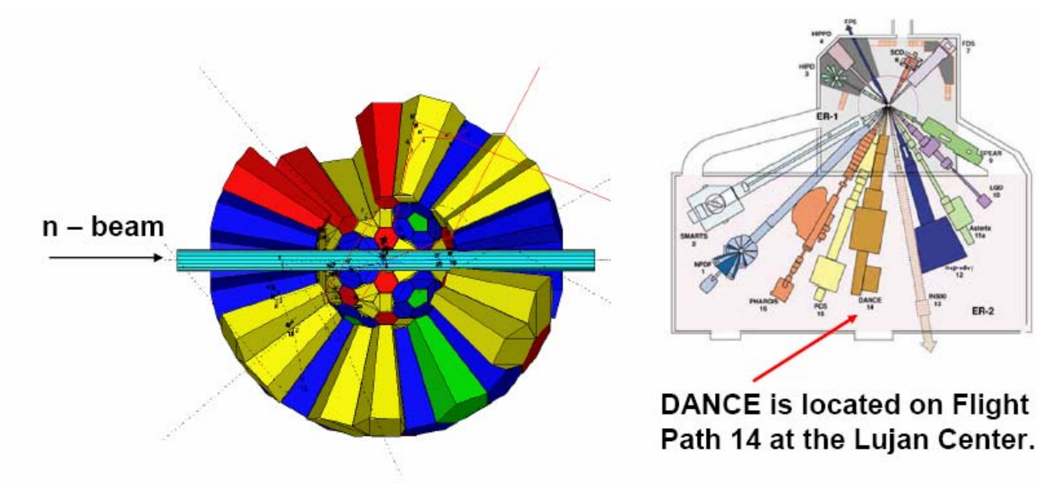
The accurate measurement of the neutron capture cross sections of ^{151,153}Eu is important for applied nuclear physics and modeling of stellar s- and r-processes in the mass A ~ 150 region. The neutron capture cross sections of stable Eu nuclei have previously been measured in several experiments, e.g. references [1-3]. The existing data in the 10-100 keV neutron energy region have discrepancy of as much as 30-40 percent. In order to resolve this discrepancy, measurements of neutron-capture cross section on $^{151,153}Eu$ nuclei have been undertaken. The experimental set-up, description of targets, and overview of analysis is given in the next section. A selection of spectra is shown to demonstrate the detailed characteristics of the system.

In addition to obtaining a precise cross section, one can utilize the high granularity of the DANCE array to obtain the γ-ray multiplicity information. Taking advantage of the high granularity, the statistical properties such as the radiative strength function can be investigated which is the focus of this paper. Models describing E1, M1 radiative strength functions are considered in section III. Results from other experiments are briefly described to demonstrate the connection of various results. The comparison between statistical model simulations and DANCE data is presented in section IV with concluding remarks in section V.

II. EXPERIMENTAL DESCRIPTION

The experiment was performed using the DANCE array located at the flight path 14 at Lujan Center at the Los Alamos Neutron Science Center (LANSCE). The DANCE array is a 4π γ-ray calorimeter that consists of 160 barium fluoride crystals, Fig. 1.

FIGURE 1. The DANCE array (on the left) consists of 160 BaF_2 crystals covering a nearly 4π solid angle. There are four different shapes each covering the same area. On the right, the schematic view of the Lujan neutron scattering center is shown.

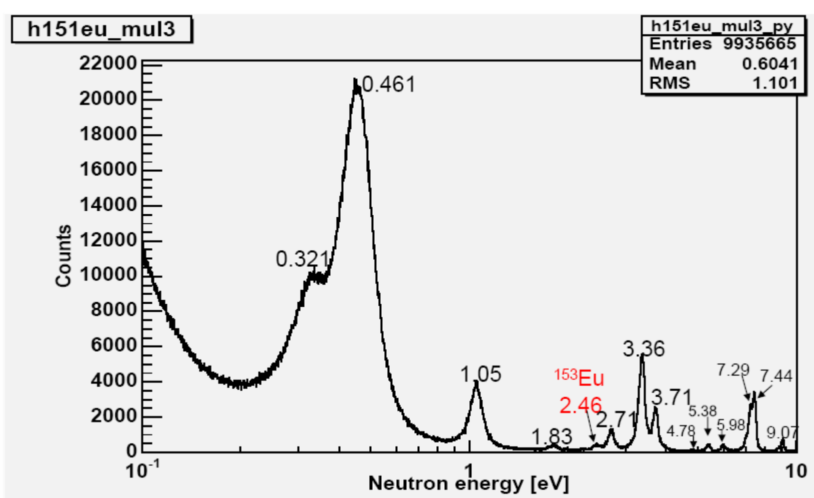


DANCE is used for (n,γ) cross section measurements on stable and unstable nuclei. The fast timing response of BaF_2 scintillators allows the measurement of cross section of short-lived nuclei. The high efficiency enables the measurement of small cross sections. Although it was not crucial in case of stable Eu where the targets are stable and capture cross section is large, the DANCE array is well suited for capture cross section measurements of rare and/or small samples. The neutron beam with E_n = 10 meV - 100 keV with the repetition rate 20 Hz was provided by the spallation neutron source at LANSCE. The flight path length is 20 meter. The neutron energy is determined by the time-of-flight technique. The stable $^{151,153}Eu$ targets with thicknesses 0.836 ± 0.040 mg/cm^2 and 1.06 ± 0.05 mg/cm^2 and enrichment 96.83 % and 98.76 %, respectively, were used. Both targets were mounted on a Be backing.

To extract the maximum amount of information from the detector, the DANCE data acquisition system relies on waveform digitization. Each BaF_2 crystal is connected to a channel in two Acqiris-4 digitizers. One of the most important responsibilities of the digitizers is a time synchronization of detectors. The description of the DANCE DAQ is given in reference [4]. The details of various background and methods of suppression are described in reference [5].

Event by event data analysis was performed offline. After the background subtraction, the spectra for each multiplicity are obtained as function of the summed energy or the γ-ray energy. These spectra are compared with the simulation. The most dominant multiplicities around the reaction Q-value $Q = E_n + B_n$, where B_n is the neutron binding energy in the compound nucleus, are 3 and 4. For the low summed-energy region, the cluster multiplicity 1 spectrum dominates because most counts with the cluster multiplicity 1 are due to scattered neutrons. Scattered neutrons that are captures in BaF_2 crystals give localized signals which are counted as one cluster. The sum energy spectra consist of summed energy of events occurred within the specified time window. In an ideal world, that should provide a δ-function-like peak around the Q-value of the reaction. However, in practice the peak is shifted slightly to the left to lower energy due to detector threshold and energy loss to the internal conversion. Resonances are well resolved in the neutron energy spectrum. Fig. 2-A shows the resonances in ^{152}Eu.

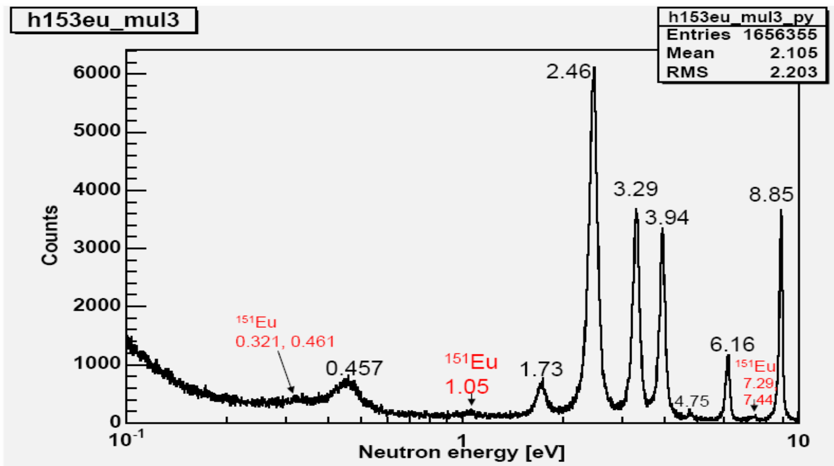
FIGURE 2-A. Resonances in the $^{151}Eu(n,\gamma)$ reaction. The spectrum with the γ-ray multiplicity 3 is shown.



All resonance energies are previously known [6]. For some of the resonances the radiative widths are not previously measured. The resonance at 2.46 eV is due to

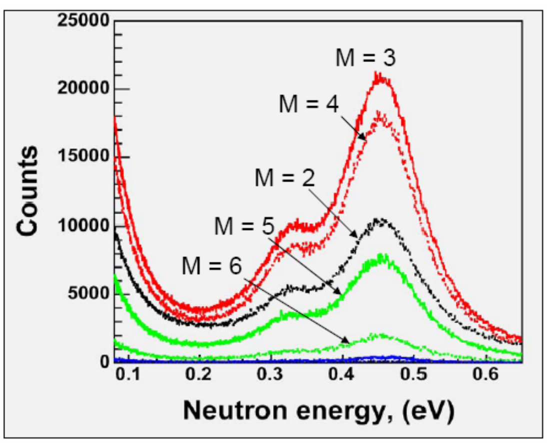
3.17% ^{153}Eu trace in the main sample. Similarly, in the neutron energy spectrum from ^{153}Eu(n,γ), in addition to all known resonances in ^{154}Eu [6], resonances due to 1.24% ^{151}Eu are observed (Fig. 2-B).

FIGURE 2-B. Resonances in the ^{153}Eu(n,γ) reaction. The spectrum with the γ-ray multiplicity 3 is shown.



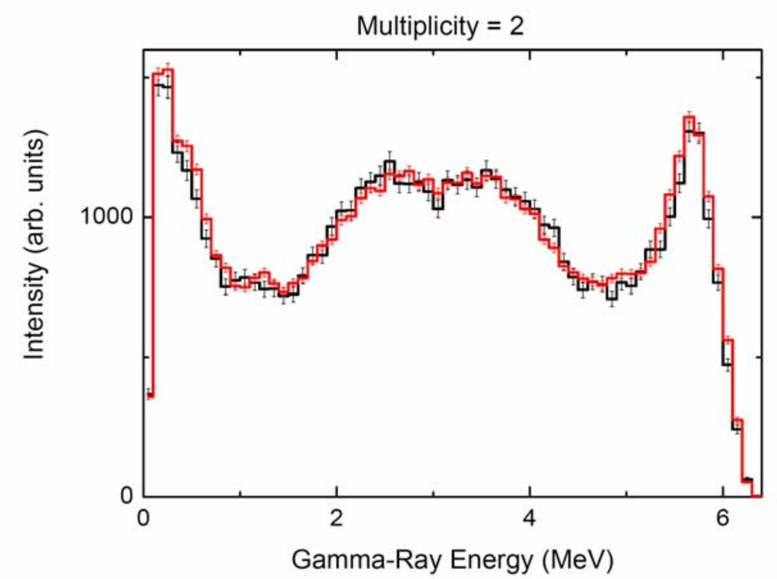
Taking advantage of the high granularity of the DANCE detector, events for each multiplicity can be separated as function of neutron energy. As an example, the first two resonances for ^{151}Eu(n,γ) are shown in Fig. 3.

FIGURE 3. The first two resonances in the ^{151}Eu(n,γ) reaction. Events with different γ-ray multiplicities can be separated for each resonance. The most dominant are multiplicities 3 and 4.



It is then possible to gate on various neutron energy region and pick out the partial spectrum events for each multiplicity. Such a partial spectrum can be studied as a function of the summed γ-ray energy, or as a function of the individual γ-ray energy. In Fig. 4. the multiplicity 2 events are plotted as a function of the individual γ-ray energy. The Q-value of the reaction is fixed, and cascades consisting of two-step transitions are selected, thus the multiplicity 2 spectrum is symmetric around the center as expected. The peak on the right hand side is slightly broader than the peak on the left due to the poorer detector resolution for higher energy γ-rays.

FIGURE 4. The multiplicity 2 spectrum. The black histogram represents on-resonance data, the neutron energy gated around the first two resonances in the ^{151}Eu(n,γ) reaction E_n = 0.24 – 0.65 eV. The red histogram represents off-resonance region where the neutron energy gated on E_n = 0.013 – 0.03 eV.



The shape of the two spectra from on-resonance and off-resonance regions is very similar reaffirming the notion of statistical description. The neutron strength function near the neutron binding energy is dominated by the s-wave strength. The compound nuclear states which are the initial states are very similar in nature, therefore the decay cascades are similar.

In this section, various spectra from DANCE data are shown to demonstrate the possible ways to emphasize the different aspects of the rich information collected with this detector. In the next section, the radiative strength function is defined and different models and experimental results are briefly described. The multiplicity 2 and 3 spectra are then compared with the simulation using various models.

III. RADIATIVE STRENGTH FUNCTION

The radiative strength function, also known as the γ-ray strength function is defined [7] as

$$f_{XL}(E_\gamma) = \frac{\left\langle \Gamma_{\gamma if} \right\rangle}{E_\gamma^{2L+1} D_i}, \qquad (1)$$

where $\left\langle \Gamma_{\gamma if} \right\rangle$ is the average partial radiative width for transition from an initial state *i* to a final state *f*, E_γ is the energy of transition, and D_i is the level spacing of the initial states. The radiative strength function $f_{XL}(E_\gamma)$ is related to the γ-ray transmission coefficient T_{XL} for γ transitions with multipolarity XL by

$$T_{XL}(E_\gamma) = 2\pi E_\gamma^{2L+1} f_{XL}(E_\gamma)\,. \tag{2}$$

Most experimental data for the RSF is from the study of photoabsorption cross sections [8, 9]. Other methods involving radiative neutron capture such as the spectrum fitting method [10] and the two-step cascade method [11, 12] provide additional information about the RSF for high-energy transitions. The investigation of primary γ-rays of different multipolarities [13, 14] and the sequential extraction method [15] are also used for obtaining experimental information for the RSF.

One of the most commonly used theoretical models is the Lorentzian function for the Giant Electric Dipole Resonance (GEDR), given by

$$f_{E1}(E_\gamma) = \frac{1}{3\pi^2\hbar^2c^2}\frac{\sigma_{E1}E_\gamma\Gamma_{E1}^2}{(E_\gamma^2 - E_{E1}^2)^2 + E_\gamma^2\Gamma_{E1}^2}\,, \tag{3}$$

where σ_{E1}, E_{E1}, Γ_{E1} are the cross section, energy centroid, and width of the GEDR. The Eq. 3 is valid for spherical nuclei. For deformed nuclei, experimental data can be fit as a superposition of two Lorentzians. A similar expression can be written for the Giant Magnetic Dipole (or Spin-flip) Resonance (GMDR) [13, 16]. This model is based on the Brink-Axel hypothesis which assumes the same giant-dipole resonance as the one built on the ground state can be built on each excited states. In other words, the giant-dipole resonance is assumed to be independent of the nuclear temperature. Moreover, although the GEDR describes data at higher transition energies, it does not adequately describe the data for low energy γ-rays [17]. To explain the non-zero limit of the RSF for $E_\gamma \to 0$, models based on the Fermi liquid theory were developed [18, 19] that give an energy and temperature dependent damping width of the GEDR

$$\Gamma_{E1}(E_\gamma, T) = \frac{\Gamma_{E1}}{E_{E1}^2}(E_\gamma^2 + 4\pi^2T^2)\,, \tag{4}$$

where the nuclear temperature for thermal neutron capture is evaluated by

$$T = \sqrt{(B_n - E_\gamma - \Delta)/a}\,, \tag{5}$$

And Δ is the pairing energy and a is the level density parameter. The strength function model developed by Kadmenskiĭ, Markushev, and Furman (KMF) is given by

$$f_{E1}(E_\gamma) = \frac{1}{3\pi^2\hbar^2c^2}\frac{0.7\sigma_{E1}\Gamma_{E1}^2(E_\gamma^2 + 4\pi^2T^2)}{E_{E1}(E_\gamma^2 - E_{E1}^2)^2}\,, \tag{6}$$

In addition to the GEDR and GMDR, the low energy ($E_\gamma \sim 3$ MeV) mode with the Lorentzian shape is considered for the total RSF. The experimental indication of the low energy mode has been observed in several types of measurements.

In the so-called Oslo method [20], nucleus is excited by the charged particle induced reaction. A matrix that consists of the first transition of the cascade is obtained by the sequential extraction method [21]. This matrix is referred to as a first-generation matrix. Consequently, the level density and radiative strength function are obtained simultaneously [22]. In many deformed rare earth nuclei studied with the Oslo-method, the bump structure in the radiative strength function at $E_\gamma \sim 3$ MeV is observed and is identified as a pygmy resonance [23, 24]. In the case of even-even deformed nuclei ^{170,172}Yb, the pygmy resonance appears to be split into two components [25]. The pygmy resonance is modeled by the Lorentzian and the multipolarity is assigned to be an M1 supported by the additional two-step cascade experiments [26].

In another set of experiments by a nuclear resonance fluorescence (NRF), a resonance mode at around the same energy, $E_\gamma \sim 3$ MeV is observed [27]. The multipolarity is unambiguously determined as an M1. The physical phenomenon that gives rise to such a mode is referred to as a scissors mode hence the resonance at $E_\gamma \sim 3$ MeV is called a scissors mode (SM) resonance. In the NRF experiments, the even-odd, and even-even nuclei are investigated.

The nuclear mass dependences of the energy of the resonance from above two sets of experiments do not agree. In addition, the total strengths of the pygmy resonance observed in the Oslo-type experiments are larger than the strength observed by the NRF by more than a factor of two. Therefore, it is unclear whether the same physics phenomenon explains both effects fully.

In the so called two-step cascade (TSC) method, de-excitation of nucleus following the thermal neutron capture is studied [28]. In this study, the SM resonance is also observed however the strength is again much greater than that of observed in the NRF experiments. From the TSC and an additional experiment using the 4π calorimeter similar to DANCE at Forschungszentrum Karlsruhe, it was found that a 3-MeV resonance in ^{163}Dy is a SM resonance and it is built on all excited levels [29].

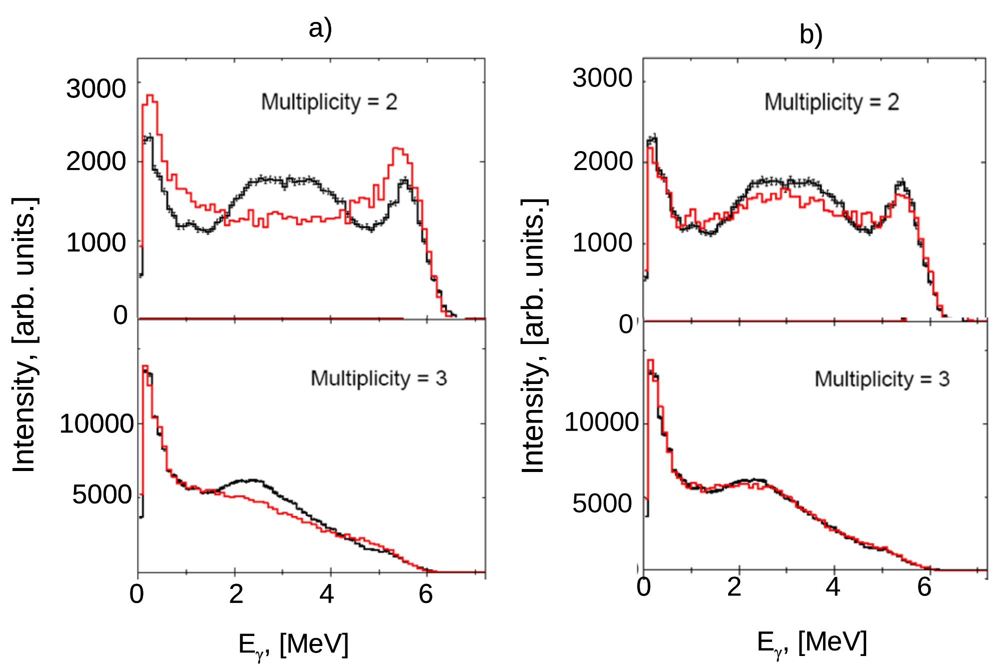
DANCE data reveal similar phenomenon in the statistical γ-ray decay cascade of Eu nuclei. The description of the simulation of the cascade and comparison between data and simulated spectrum are discussed in the next section.

IV. SIMULATION AND MODELING

Experimental data obtained from the DANCE detector can be compared with an outcome from simulations performed by adjacent DICEBOX/GEANT simulations. The Monte Carlo code DICEBOX [28] generates γ-ray cascades initiating at the neutron capturing state, that is a s-wave resonance in our case, and terminating at the ground state following the rules of the extreme statistical model. The level system of the nucleus and the associated decay scheme are artificially generated in the code according to an adopted level-density model and models of radiative strength functions for different types of transitions are assumed. Each set of the generated level structure and the decay scheme are called a nuclear realization. The level structure below some critical energy E_{crit} about 400 keV in odd-odd Eu nuclei is taken from literature and kept fixed [30]. Above E_{crit}, the level density and decay scheme are assumed to follow statistical rules. Many nuclear realizations are simulated. Introducing the technique of precursors, as described in [28], the code DICEBOX offers the unique feature of rigorous simulation of the residual Porter-Thomas fluctuations of any cascade-related quantity. Another very important feature of the code is the proper treatment of conversion electrons which is a considerable factor for the decay of Eu nuclei.

Cascades produced by the DICEBOX code in the list mode serve as an input for GEANT simulation of the detector response to these cascades. Various types of simulated spectra can be produced by the simulation procedure described above. Simulation and data for sum-energy spectra and γ-ray spectra for events for various multiplicities with deposited sum-energy close to Q-value of the (n,γ) reaction are compared. Comparisons between data from the Eu experiments at DANCE and simulation are shown in Fig. 5. Multiplicity 2 and 3 spectra are shown as a function of the γ-ray energy. The bump structure in the center of the multiplicity 2 spectrum, and near 2.4 MeV in the multiplicity 3 spectrum is identified to be due to the existence of the low-energy mode resonance.

FIGURE 5. Comparison between data and simulation. The black histograms represent data from the neutron energy gated around the first two resonances in the ^{151}Eu(n,γ) reaction E_n = 0.24 – 0.65 eV. The red histograms represent simulations a) without postulating any resonance and 2) with postulating an M1 resonance.



In both a) and b), the Back-Shifted Fermi gas model for the level density is employed. For the radiative strength function, the KMF model for the E1 GEDR given by Eq. (6), and the M1 spin-flip GMDR given by the Lorentzian similar to Eq. (3) are chosen. Without introducing any low energy resonance near 3 MeV, an agreement between data and simulation for all multiplicities is poor. As an example of poor fit, multiplicity 2 and 3 spectra are shown in the two graphs on the left in Fig. 5. Assuming an E1 resonance near 3 MeV does not improve the fit. Assuming an M1 resonance improves the fit significantly. Variation of the parameters of the M1 resonance yields better fit at E_γ = 2.6 MeV with width Γ_γ = 1.6, with a good agreement in the multiplicity 3 spectrum, an improved but not satisfactory agreement in the multiplicity 2 spectrum as shown in the right two graphs in Fig. 5. Similar resonance is also observed in the case of ^{153}Eu. The complicated level structure of odd-odd compound systems ^{152,154}Eu requires further refinement in the consideration of effect of isomers and varying deformation as a function of excitation energy.

V. CONCLUSION AND OUTLOOK

The 4π γ-ray calorimeter DANCE is utilized for the study of statistical decay cascade following the neutron capture on stable Eu targets. The high granularity of the detector allows one to look closely at cascade with specified number of transitions. The decay cascade is simulated using the statistical code DICEBOX taking into account the detector response function with usage of the GEANT code. The outcome of the simulation is compared with the experimental spectra. A concentration of γ-ray strength is identified at present as manifestation of the scissors-mode like mechanism in odd-odd Eu nuclei. Further developments in the analysis and simulation are underway.

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REFERENCES

[1] R. L. Macklin and P. G. Young, Nucl. Sci. Eng. **95**, 189 (1987).
[2] V.A. Konks, Yu. P. Popov, and Yu. I. Fenin, Sov. J. Nucl. Phys. **7**, 310 (1968).
[3] V. N. Kononov et al., Proc. 4th All-Union Conf. Neutron Physics, Kiev, April 18-22, (1976).
[4] J. M. Wouters et al., to be published in the Proceedings of the 14th IEEE-NPSS Real-Time Conference, (2005).

[5] R. Reifarth et al., Nucl. Inst. Methods Phys. Res. A **531**, 530 (2004).
[6] F. Rahn et al., Phys. Rev. C **6**, 251 (1972).
[7] J. M. Blatt and V. F. Weisskopf, Theoretical Nuclear Physics, Wiley, New York , (1952).
[8] B. L. Berman and S. C. Fultz, Rev. Mod. Phys. **47**, 713 (1975).
[9] Samuel S. Dietrich and Barry L. Berman, At. Data Nucl. Data Tables **38**, 199 (1988).
[10] E. D. Earle et al., Can. J. Phys. **52**, 989 (1974).
[11] F. Bečvář, P. Cejnar, R. E. Chrien, and J. Kopecky, Phys. Rev. C **46**, 1276 (1992).
[12] F. Bečvář, P. Cejnar, J. Honzátko, K. Konečný, I. Tomandl, and R. E. Chrien, Phys. Rev. C **52**, 1278 (1995).
[13] J. Kopecky and R. E. Chrien, Nucl. Phys. **A468**, 285 (1987).
[14] W. V. Prestwich et al., Z. Phys. **A315**, 103 (1984).
[15] G. A. Bartholomew et al., Can. J. Phys. **48**, 687 (1970).
[16] A. Richter, Prog. Part. Nucl. Phys. **34**, 261 (1995).
[17] Y. P. Popov, Fiz. Elem. Chastits. At. Yadra **13**, 1165 (1982), [Sov. J. Part. Nucl. **13**, 483 (1982)].
[18] S. G. Kadmensiĭ, V. P. Markushev, and V. I. Furman, Yad. Fiz. **37**, 277 (1983), [Sov. J. Nucl. Phys. **37**, 165 (1983)].
[19] V. K. Sirotkin, Yad. Fiz. **43**, 570 (1986), [Sov. J. Nucl. Phys. **43**, 362 (1986)].
[20] M. Guttormsen et al., Phys. Scr. **T32**, 54 (1990).
[21] A. Schiller et al., Nucl. Inst. Methods Phys. Res. A **447**, 498 (2000).
[22] M. Guttormsen et al., Nucl. Inst. Methods Phys. Res. A **374**, 371 (1996).
[23] A. Voinov et al., Phys. Rev. C **63**, 044313 (2001).
[24] M. Guttormsen et al., Phys. Rev. C **68**, 064306 (2003).
[25] U. Agvaanluvsan et al., Phys. Rev. C **70**, 054611 (2004).
[26] See A. Schiller's contribution in this proceeding.
[27] A. Zilges et al., Nucl. Phys. **A519**, 848 (1990).
[28] F. Becvar, Nucl. Instr. Methods A **417**, 434 (1998).
[29] M. Krtička et al., Phys. Rev. Lett. **92**, 172501 (2004).
[30] T. Von Egidy et al., Z. Phys. A **286**, 241 (1978).